

1 FLEXIBLE MEMBRANE ENCAPSULATED STRAIN

2 MEASUREMENT INSTRUMENT AND METHOD OF MANUFACTURE

3
4 RELATED APPLICATIONS

5 This application is related to U.S. Application No.
6 09/715,371 to Crockford which is incorporated herein by
7 reference.

8
9 FIELD OF THE INVENTION

10 This invention relates to the field of testing equipment
11 and, particularly, to test cells for soil samples.

12
13 BACKGROUND OF THE INVENTION

14 Geotechnical and paving materials such as soil and asphalt
15 are often tested to obtain their engineering properties in
16 axisymmetric triaxial testing cells. The specimen shape is
17 usually a solid right circular cylinder. In rare cases, a
18 hollow cylinder is used. The triaxial cells allow simultaneous
19 pressurizing of the specimen periphery and deviatoric stress
20 loading in one or more directions, usually the axial direction.
21 The pressurizing media include a range of fluids such as air,
22 mineral oil, or water though other fluids may be employed.

23 Since the test specimens are porous in nature, and the
24 porosity is often structured such that the specimen is

1 permeable to the pressurizing medium therefore, it is necessary
2 to introduce an impermeable seal around the specimen to isolate
3 the mechanical effect of confining stress. In order to allow
4 the specimen to change shape during testing, this impermeable
5 seal must be flexible, usually made of polymers such as latex,
6 nitrile or silicone for testing paving materials and soils,
7 while it may be a metal (e.g. copper) jacket for testing solid
8 rock.

9 Displacement measurement(s) are usually necessary for
10 computing the desired engineering properties from the stresses
11 and strains (engineering strain is related to displacement
12 through a very simple equation). It is often impossible to use
13 the traditional resistance strain gauge in this application
14 because (a) the specimen sometimes cannot be instrumented with
15 a strain gauge that relies on adhesives, (b) large strains are
16 difficult to precisely measure with typical resistance strain
17 gauges, and (c) the surface void texture causes the strain
18 gauge to be inaccurate. The axis of the cylinder is usually
19 vertical, so the deviatoric loading and the related strains are
20 parallel to this axis. Therefore, the vertical displacement
21 measurements are required for all but the most basic
22 engineering properties e.g., simple material strength does not
23 require the measurement of strain, it only requires measurement
24 of stress. Vertical strains combined with horizontal strains

1 can be used for determining Poisson's ratio and dilation
2 parameters.

3 The horizontal or radial strain may be measured at a
4 number of points on the surface of the cylinder, or by one or
5 more circumferential measurements which has the advantage of
6 reducing the number of transducers and improving the signal to
7 noise ratio of a given transducer, if it is an analog device,
8 or by other means such as volume change or optical
9 measurements.

10 U.S. Patent No. 5,025,668 issued to Sarda et al. has
11 instrumentation which is externally referenced. Such an
12 apparatus has limitations: (1) it is not immune from end
13 effects, and (2) it does not uncouple the vertical from the
14 horizontal displacement. End effects alter strain measurements
15 from the true value because the specimen deforms more like a
16 whiskey barrel than like a right circular cylinder. The end
17 effects are worse (a) when the friction between the specimen
18 end and the loading platen is high, as is the case with many
19 soils and virtually all asphalt materials, (b) when the
20 measurement is taken with a gauge length that spans the whole
21 specimen height from end to end, (c) when the specimen is
22 short, and (d) when the properties at the ends of the specimen
23 are different from the true properties of the specimen in the
24 middle portion of the specimen for example, molded specimens

1 tend to have somewhat different densities and air void
2 properties close to the ends. The end effects often affect the
3 vertical strain measurements more than the radial measurements.

4 If radial measurements are taken, they should be uncoupled
5 from the vertical movement. Since the radial measurements are
6 usually very small in relation to the vertical on materials
7 having Poisson's ratio smaller than 0.5, friction at the end of
8 the shaft in contact with the specimen can introduce bending
9 and/or binding in the shaft, causing the measured radial
10 deflection to be incorrect.

11 U.S. Patent No. 4,579,003 issued to Riley also
12 illustrates instrumentation that is externally referenced.
13 Riley discloses an improvement over the device disclosed by
14 Sarda in that the instrumentation is internal to the triaxial
15 cell, but it is still external to the specimen. At the very
16 small displacements commonly measured with soils and asphalt,
17 any interface between any material other than the material
18 being tested and some other material ,such as a metal or
19 polymer platen, can cause enough deformation under load to
20 totally mask the correct strain measurement. Therefore,
21 measuring between the stages as disclosed by Riley is likely to
22 produce better measurements than Sarda's device.

1 SUMMARY OF THE INVENTION

2 Disclosed is a flexible membrane for use in test cells to
3 measure a property of a material including stress, strain,
4 temperature, deformation, moisture content, etc.. The test
5 cells include instrumentation within the thickness of the
6 membrane to accurately measure stresses causing deformation of
7 the sample. A test specimen may be enclosed within the
8 membrane to isolate the specimen from testing fluids in the
9 test chamber. The instrumentation may measure axial stresses
10 and strains or radial stresses and strains or a combination
11 thereof.

12 U.S. Patent Application No. 09/715,371 submitted by the
13 Applicant and incorporated herein by reference, notes several
14 instrumentation means. When mounting of the instrumentation is
15 done by mechanically attaching to the membrane, moment analyses
16 are useful as described in the application. While moment
17 analyses are always useful, in the particular case of an
18 application in which the vertical displacement measurement
19 means is either (a) the only measurement means, or (b) is
20 capable of being completely separated from the radial
21 measurement means in a combined measurement configuration, it
22 is possible to make an even simpler instrumentation means by
23 making the instrumentation an integral part of the membrane.

24 Therefore, it is an objective of this invention to provide

1 a flexible membrane for intimate contact with the surface of
2 the specimen to isolate the specimen from the testing fluids in
3 the test cell and permit the specimen to deform in response to
4 testing stresses.

5 It is another objective of this invention to provide
6 instrumentation integrally incorporated within the membrane to
7 quantify and record the strains.

8 It is yet another objective of this invention to provide
9 an instrumented membrane to measure radial or axial strains,
10 alone.

11 It is a further objective of this invention to provide
12 instrumentation to measure axial and radial stresses. The
13 circumferential approach would be the most appropriate method
14 for measuring radial properties using the instrumentation and
15 one skilled in the field will be able to extend the teaching
16 directed toward the vertical measurement presented herein to
17 include both the vertical and the horizontal or only the
18 horizontal in various embodiments.

19 It is still another objective of this invention to provide
20 instrumentation in the membrane to measure the temperature,
21 moisture content and/or soil suction of a specimen during a
22 test.

23 Other objectives and advantages of this invention will
24 become apparent from the following description taken in

1 conjunction with the accompanying drawings wherein are set
2 forth, by way of illustration and example, certain embodiments
3 of this invention. The drawings constitute a part of this
4 specification and include exemplary embodiments of the present
5 invention and illustrate various objects and features thereof.

6

7 BRIEF DESCRIPTION OF THE DRAWINGS

8 Fig. 1 is a perspective view of instrumented membrane for
9 axial measurements only;

10 Fig. 2 is a partial section view of instrumented membrane
11 for axial measurements only;

12 Fig. 3 is a perspective of the flexible cord;

13 Fig. 4 is a perspective of the mounting hardware for
14 independent circumferential measurement;

15 Fig. 5 is a perspective of the mounting hardware for
16 combination vertical and circumferential measurement;

17 Fig. 6 is a perspective view of instrumented membrane for
18 combination axial and circumferential measurements;

19 Fig. 7 is a partial section view of instrumented membrane
20 for combination axial and circumferential measurements;

21 Fig. 8 is a perspective of an alternate embodiment of the
22 membrane for combination measurements with a temperature probe
23 and moisture content chamber;

24 Fig. 9 is an exploded view of membrane manufacturing mold;

1 Fig. 10 is a perspective of the circumferential
2 measurement mounting hardware; and

3 Fig. 11 is a perspective of an alternate embodiment of
4 mold hardware for circumferential measurement capability.

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6 DETAILED DESCRIPTION OF THE INVENTION

7 Fig. 1 shows the straight tube portion 52A of the membrane
8 and Fig. 2 shows a section view through the membrane and one of
9 the vertical measurement instruments. In a constant thickness
10 version of the membrane, the thickness of 52A in Fig. 1 is
11 thicker than the cross section dimension of the displacement
12 sensor, which requires its minimum thickness to be larger than
13 that necessary to produce the pressure barrier alone. The
14 thickness may vary in other embodiments, such as that produced
15 by the fabrication mold assembly, discussed below in the
16 manufacturing method portion of this application. The membrane
17 section shown in Figs 1 and 2 show a cavity 52B that is molded
18 into the membrane material, such as silicone or latex rubber,
19 or other polymeric materials, and this cavity receives the
20 LVDT (linear variable differential transformer) type
21 displacement transducer 76A, 76B, and 76C. The cavity 52B is
22 tubular in nature, but it is not centered within the wall
23 thickness of the membrane. By offsetting the cavity toward the
24 outside surface of the membrane, the large diameter portions of

1 the cavity are actually open to the outside surface of the
2 membrane by the slit 52C in Fig. 1.

3 The inside diameter of the membrane is, therefore,
4 continuous so that no leakage of the pressurizing fluid occurs
5 from one side of the membrane to the other. Although the
6 outside slits are provided to make it possible to insert the
7 parts of the transducer into the cavity after the membrane has
8 been molded, it would be possible to mold the transducer into
9 the rubber during manufacture. However, there are wires that
10 come into an LVDT type device that are not shown at 76A, and
11 these wires may make membrane manufacture with the transducer
12 in place during the manufacturing somewhat cumbersome.
13 Further, individual molded-in transducers, even if they were
14 wireless, would be difficult to replace without destroying the
15 membrane. Of course, the instrumented membranes may be a
16 single use type or capable of multiple tests. In the
17 preferred embodiment, the LVDT type sensor would be placed in
18 the cavity after the membrane has been manufactured.

19 The temperature probe 66 may also be molded in the
20 membrane, as well as, the screen 67A of the moisture content
21 chamber 67B, shown in Fig. 8. The moisture content chamber 67B
22 may have an instrument 67C therein which measures soil suction
23 or soil potential. A source of these dielectric probes or
24 tensiometers is Soilmoisture Equipment Corp in California.

1 The screen 67A may be a semipermeable membrane to maintain
2 isolation of the sample from the testing fluid or in the event
3 the walls of the moisture content chamber 67B are made
4 impervious the screen 67A may be a sieve.

5 The LVDT type sensor usually comprises three or more
6 parts: a transformer body 76A, a core and core rod extension
7 76B and a piece of anchoring hardware 76C used in conjunction
8 with the core rod extension to establish the desired gauge
9 length for the measurement. Since these three components can
10 be separated, and since the membrane is usually a flexible
11 elastomer such as a silicone or latex rubber or a cast
12 urethane, it is possible to (a) insert the body of the LVDT
13 into the upper or lower slit 52C in the membrane and allow the
14 wires to hang out of the slit, and (b) insert the other
15 components into the other slit in the membrane. Once in place,
16 the friction between the inside surface of the membrane and the
17 outside diameter of the specimen under test will allow
18 measurement of the vertical deflection of the specimen under
19 load. The changing distance between 76C and 76A when the
20 specimen experiences strain due to the axial load generates a
21 measurable displacement signal.

22 The preferred embodiment would use multiple sets of
23 vertical LVDTs for example, three sets of parts 76A, 76B, and
24 76C arranged in a pattern at 120 degree angle increments about

1 the central axis of a cylindrical specimen, although fewer or
2 more LVDTs would be possible. Four sets would be preferred, if
3 the specimen were rectangular instead of cylindrical.

4 In order to measure radial strain using a circumferential
5 measurement on a cylindrical specimen, the preferred embodiment
6 comprises a flexible cord or ribbon 79 shown in Fig. 3,
7 mounting hardware 77 shown in Fig. 4, or 76D shown in Fig. 5,
8 and a spring-loaded LVDT 78, 80, and/or 82, shown in Fig. 6.
9 Mounting hardware 77 would be mounted in an additional membrane
10 cavity 84. The flexible cord may be of any cross sectional
11 shape. If the available clearance space is very small, flat or
12 oblong shapes may be improvements over circular cross sections
13 to reduce stress on the membrane.

14 For a single radial measurement, the preferred embodiment
15 would position the circumferential measurement components at
16 the mid location, as shown by LVDT 80. As shown in Fig. 7,
17 this flexible cord should pass freely through a cavity 86 in
18 the membrane that is closer to the inside surface of the
19 membrane than the core rod 76B. In Fig. 4, LVDT 80 would be
20 mounted in the larger of the two holes 77A in the mount 77, one
21 end of the flexible cord would be attached to the LVDT and the
22 other end of the cord would be attached in the smaller hole 77B
23 using an adhesive. The two holes in the mounting hardware 77
24 should be fabricated at an angle that will allow the two ends

1 of the flexible cord that are attached at the LVDT and at 77B
2 to maintain tangency to the circle they define in the membrane
3 cavity as closely as possible.

4 For two radial measurements, one embodiment would comprise
5 two such component assemblies positioned above and below the
6 mid-height at some distance that would give a representative
7 picture of the radial deformation if it were to deform in a
8 barrel shape instead of a perfect right circular cylinder. In
9 the preferred embodiment, using either two or three radial
10 measurements, the vertical anchor hardware 76C could be
11 modified to perform double duty as a combination radial LVDT
12 holder and anchor for the vertical LVDT 76D. Using the double
13 duty configuration along with the mid- height mount enables
14 three radial measurements to be taken that can be averaged or
15 used independently to better quantify the overall shape during
16 deformation. The combination unit 76D, incorporates features
17 additional to the basic features that comprise the standard
18 anchor unit 76C, including a mounting feature such as a hole
19 76E to receive the spring-loaded radial LVDT, and a notch 76F.
20 The notch 76F is used to anchor one end of the cord 79 for
21 example, with an adhesive or by crimping, in the anchor that
22 also has the LVDT mounted in it. At other locations around the
23 120 degree pattern, the notch is simply a clearance notch that
24 allows the cord 79 to pass through unobstructed.

1 While there are various sophisticated methods of forming
2 polymers, a very simple method of manufacturing membranes with
3 cavities is illustrated in Fig. ~~8~~⁹. When assembled, the device
4 illustrated in Fig. 9 is filled with an appropriate quantity of
5 raw membrane material, closed on the ends, and inserted into a
6 device that can be rotated around the central axis, such as a
7 lathe. The centrifugal force during rotation will generate an
8 evenly distributed layer of material on the inside of the tube,
9 simultaneously filling the areas around the LVDT cavities.

10 Various flexible materials can be used, and a chemical
11 mold release agent may or may not be necessary to enable
12 release of the cured membrane material from the mold surfaces.
13 Dow Corning's two part Silastic material has been found
14 suitable for a membrane material. This material cures faster
15 under heat which allows reduction of the time necessary to
16 rotate the mold.

17 In Fig. 9, the mold tube 200 has an inside diameter that
18 is determined by the specimen diameter and the desired membrane
19 thickness. The outside diameter of the tube is determined by
20 the diameter of the measurement device. One or more flats 202
21 are fabricated on the outer diameter of the mold. A mold plate
22 204 will be attached to the mold flats with plate attachment
23 screws 206 after the instrument cavity components 210A, 210B,
24 and 210C have been attached to the plate with instrument cavity

1 mold screws 208.

2 The instrument cavity components 210A, 210B, and 210C are
3 dimensionally designed to receive the instrument components
4 76A, 76B, and 76C. Instrument cavity shaft 210B must be larger
5 in diameter than instrument shaft 76B because the instrument
6 shaft must be free to move in the cavity without friction.
7 Leakage of the pressurizing medium through the slits 52C allows
8 for pressure relief/equalization in the shaft cavity so that it
9 neither appreciably inflates nor collapses on the instrument
10 shaft during pressurization. The lower and upper mold body
11 components 210A and 210C are preferably designed with slightly
12 smaller dimensions than the corresponding instrument parts 76A
13 and 76C so that the instrument components will be tightly held
14 in the cavity of the finished membrane. The instrument cavity
15 components 210A and 210C have a flat 212A fabricated on them
16 and one or more threaded holes 212B on the flat. Cavities for
17 different gauge lengths can be attained by attaching to the
18 different mounting holes as desired.

19 For applications only requiring vertical (i.e. axial)
20 measurements, features 214, 216, and 218 are unnecessary. For
21 a single circumferential measurement, and for applications in
22 which radial measurements do not occupy the same horizontal
23 planes occupied by the vertical cavity components 210A and
24 210C, a cavity forming wire 218 used to form the cavity 86,

1 and a support for the wire 216, 216A (also shown in another
2 view in Fig. 10) are used.

3 For applications only requiring vertical (i.e. axial)
4 measurements, and for applications in which radial measurements
5 do not occupy the same horizontal planes occupied by the cavity
6 components 210A and 210C, those components can be of the same
7 design as shown in Fig. 9.

8 For multiple circumferential measurements that require the
9 use of mounting hardware 76D, in Fig. 5, the corresponding mold
10 components require the additional support features 217B and/or
11 217C, in Fig. 10, of another embodiment. The extrusion or boss
12 217C is required only at those positions that require a
13 circumferential instrument for example, 78 and 82, and a
14 vertical anchor at the same location. The notch 217B is
15 required at all positions for which the wire 218 needs to be
16 supported on a vertical mold body component. As an example,
17 for the case of the lower wire 218 located in the plane
18 occupied by component 210A, one mold component located at 210A
19 would need both the notch 217B and the boss 217C.

20 The configuration of the other two vertical mold body
21 components located around the 120 degree pattern would only
22 require the notch 217B in order to ensure that the wire 218
23 remains in a level plane perpendicular to the axis of the
24 cylinder during the molding process and would therefore not

1 require the boss.

2 A number of embodiments of the present invention have been
3 described. Nevertheless, it will be understood that various
4 modifications may be made without departing from the spirit and
5 scope of the invention. Accordingly, it is to be understood
6 that the invention is not to be limited by the specific
7 illustrated embodiment but only by the scope of the appended
8 claims.

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